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**METHOD AND APPARATUS FOR DETERMINING COMPUTER PROGRAM  
FLOWS AUTONOMICALLY USING HARDWARE ASSISTED THREAD STACK  
TRACKING AND CATALOGED SYMBOLIC DATA**

**CROSS REFERENCE TO RELATED APPLICATIONS**

The present invention is related to the following applications entitled "APPARATUS AND METHOD FOR AUTONOMIC HARDWARE ASSISTED THREAD STACK TRACKING", serial no. 10/703,658, attorney docket no. AUS920030542US1, filed on November 6, 2003; "APPARATUS AND METHOD FOR CATALOGING SYMBOLIC DATA FOR USE IN PERFORMANCE ANALYSIS OF COMPUTER PROGRAMS", serial no. 09/613,190, attorney docket no. AUS000127US1 filed on July 10, 2000. Both related applications are assigned to the same assignee and are incorporated herein by reference.

**BACKGROUND OF THE INVENTION**

**1. Technical Field:**

The present invention relates generally to an improved data processing system and, in particular, to a method and system for processing performance data in a data processing system. Still more particularly, the present invention relates to a method, apparatus, and computer instructions for determining computer program flows autonomically using hardware assisted thread stack tracking and cataloged symbolic data.

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## **2. Description of Related Art:**

In analyzing and enhancing performance of a data processing system and the applications executing within the data processing system, it is helpful to know which software modules within a data processing system are using system resources. Effective management and enhancement of data processing systems require knowing how and when various system resources are being used. Performance tools are used to monitor and examine a data processing system to determine resource consumption as various software applications are executing within the data processing system. For example, a performance tool may identify the most frequently executed modules and instructions in a data processing system, or may identify those modules which allocate the largest amount of memory or perform the most I/O requests. Hardware performance tools may be built into the system or added at a later point in time.

One known software performance tool is a trace tool. A trace tool may use more than one technique to provide trace information that indicates execution flows for an executing program. One technique keeps track of particular sequences of instructions by logging certain events as they occur, a so-called event-based profiling technique. For example, a trace tool may log every entry into, and every exit from, a module, subroutine, method, function, or system component. Alternately, a trace tool may log the requester and the amounts of memory allocated for each memory allocation request. Typically, a time-stamped record is produced for each such event.

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Corresponding pairs of records similar to entry-exit records also are used to trace execution of arbitrary code segments, starting and completing I/O or data transmission, and for many other events of interest.

Another trace technique involves periodically sampling a program's execution flows to identify certain locations in the program in which the program appears to spend large amounts of time. This technique is based on the idea of periodically interrupting the application or data processing system execution at regular intervals, so-called sample-based profiling. At each interruption, information is recorded for a predetermined length of time or for a predetermined number of events of interest. For example, the program counter of the currently executing thread, which is an executable portion of the larger program being profiled, may be recorded during the intervals. These values may be resolved against a load map and symbol table information for the data processing system at post-processing time, and a profile of where the time is being spent may be obtained from this analysis.

Currently, determining execution flows of a computer program is often performed using software, such as trace tools described above. However, software performance trace tools are often less efficient in performance and require a larger memory footprint. A large memory footprint requires longer loading time and reduces operating efficiency of the system.

In addition, current data processing system applications or computer programs are typically built

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with symbolic data and may even be shipped to client devices with symbolic data still present in the modules. Symbolic data is, for example, alphanumeric representations of application module names, subroutine names, function names, variable names, and the like.

An application is comprised of modules written as source code in a symbolic language, such as FORTRAN or C++, and then converted to a machine code through compilation of the source code. The machine code is the native language of the computer. In order for a program to run, it must be presented to the computer as binary-coded machine instructions that are specific to that CPU model or family.

Machine language tells the computer what to do and where to do it. When a programmer writes: `total = total + subtotal`, that statement is converted into a machine instruction that tells the computer to add the contents of two areas of memory where `TOTAL` and `SUBTOTAL` are stored.

Since the application is executed as machine code, performance trace data of the executed machine code, generated by the trace tools, is provided in terms of the machine code, i.e. process identifiers, addresses, and the like. Thus, it may be difficult for a user of the trace tools to identify the modules, instructions, and such, from the pure machine code representations in the performance trace data. Therefore, the trace data must be correlated with symbolic data to generate trace data that is easily interpreted by a user of the trace tools.

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The symbolic data with which the trace data must be correlated may be distributed amongst a plurality of files. For example, the symbolic data may be present in debug files, map files, other versions of the application, and the like. In the known performance tool systems, in order to correlate the symbolic data with the performance trace data, the performance tool must know the locations of one or more of the sources of symbolic data and have a complex method of being able to handle redundancies in the symbolic data.

In addition, such correlation is typically performed during post-processing of the performance trace data. Thus, an additional separate step is required for converting performance trace data into symbolic representations that may be comprehended by a performance analyst.

The conversion of performance trace data into symbolic representations is performed at a time that may be remote to the time that the performance trace is performed. As a result, the symbolic data may not be consistent with the particular version of the computer program executed during the trace. This may be due to the fact that, for example, a newer version of the application was executed during the trace and the symbolic data corresponds to an older version of the application.

This may be especially true for applications whose symbolic data is maintained at a supplier's location with the machine code being distributed to a plurality of clients. In such a case, the supplier may continue to

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update the symbolic data, i.e. create new versions of the application, but fail to provide the newest version of the application to all of the clients. In this scenario, if a performance trace were to be performed, the symbolic data maintained by the supplier may not be the same version as the machine code on which the performance trace is performed.

Therefore, it would be advantageous to have an improved method, apparatus, and computer instructions for determining computer program flows that requires a smaller memory footprint and provides user readable results using correlated symbolic data.

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### **SUMMARY OF THE INVENTION**

The present invention provides a method, apparatus, and computer instructions for determining computer program flows autonomically using hardware assisted thread stack tracking and cataloged symbolic data. When a new or existing thread is dispatched during execution of a computer program, the present invention provides hardware control registers that assist in allocating or identifying a thread work area where call stack entries are stored for the particular thread.

With the present invention, microcode is programmed with instructions for establishing thread work areas and monitoring the execution of instructions to determine how to update the thread tracking information in the thread work area. In one mode of operation, when tracing occurs, call stack data is written to entries of the thread work area continuously. When the call stack is full, call stack data is copied by the operating system to a consolidated buffer. Thus, a full trace of the thread operation is performed.

In another mode of operation, herein referred to as the call stack mode, when a call operation is detected, call stack data is written by microcode of the processor to the entries of the thread work area. However, when a return operation is detected, call stack data is removed from the stack. Entries are pushed onto and popped from the call stack as the thread is executing. In the call stack mode, the trace application wakes up periodically to instruct the operating system or the device driver to



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copy call stack data from the thread work area to the consolidated buffer. Thus, only a sample trace of the thread operation is performed.

During or after the tracing phase, the trace application or the post-processing application may perform post-processing of the call stack data. The trace application or the post-processing application reads from the consolidated buffer. The operating system, the device driver, or a performance monitoring application then maps each thread to a process to which the thread belongs. When requested by the trace application or post-processing application, symbolic data is obtained from an indexed database matching the mapped process and address of the method/routine that is called or returned for each thread. Using the symbolic data and the call stack data, a call sequence is generated. After generating a call sequence, the trace application or post-processing application autonomically determines the corresponding computer program flow.

These and other features and advantages of the present invention will be described in, or will become apparent to those of ordinary skill in the art in view of, the following detailed description of the preferred embodiments.

**BRIEF DESCRIPTION OF THE DRAWINGS**

The novel features believed characteristic of the invention are set forth in the appended claims. The invention itself, however, as well as a preferred mode of use, further objectives and advantages thereof, will best be understood by reference to the following detailed description of an illustrative embodiment when read in conjunction with the accompanying drawings, wherein:

**Figure 1** is an exemplary pictorial representation of a distributed data processing system in which the present invention may be implemented;

**Figure 2A** is an exemplary block diagram of a server data processing system in which aspects of the present invention may be implemented;

**Figure 2B** is an exemplary block diagram of a stand-alone or client data processing system in which aspects of the present invention may be implemented;

**Figure 3** is an exemplary block diagram depicting components used to perform performance traces of processes in a data processing system;

**Figure 4** is a diagram depicting various phases in performing a performance trace of the workload running on a system;

**Figure 5A** is a flowchart illustrating an exemplary process of initiating hardware thread stack tracking in accordance with a preferred embodiment of the present invention;

**Figure 5B** is a flowchart illustrating an exemplary process of writing hardware thread tracking information

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to the allocated thread work area as events occurs in one mode of operation in accordance with a preferred embodiment of the present invention;

**Figure 5C** is a flowchart illustrating an exemplary process of writing hardware thread tracking information to the allocated thread work area as events occurs in call stack mode of operation in accordance with a preferred embodiment of the present invention;

**Figure 6** is a diagram illustrating primary operational components according to one exemplary embodiment of the present invention;

**Figure 7** is a flowchart outlining an exemplary operation of the data processing system of the present invention when dynamically generating an indexed database of symbolic data based on performance trace data stored in the trace buffer in accordance with a preferred embodiment of the present invention;

**Figure 8A** is a diagram illustrating interactions between components during post-processing by a trace application in accordance with a preferred embodiment of the present invention;

**Figure 8B** is a diagram illustrating interactions between components during post-processing by a post-processing application in accordance with a preferred embodiment of the present invention;

**Figure 9A** is a flowchart process illustrating an exemplary process of determining computer program flow autonomically using thread stack tracking information and cataloged symbolic data when post-processing is performed

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during profiling in accordance with a preferred embodiment of the present invention;

**Figure 9B** is a flowchart process illustrating an exemplary process of determining computer program flows autonomically using thread stack tracking information and cataloged symbolic data when post-processing is performed after profiling in accordance with a preferred embodiment of the present invention; and

**Figure 10** is a diagram illustrating an example indexed symbolic database, example call stack entries, and an example call sequence in accordance with a preferred embodiment of the present invention.

**DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT**

The present invention provides a method, apparatus, and computer instructions for determining computer program flows autonomically using hardware assisted thread stack tracking and cataloged symbolic data. The present invention may be implemented in a stand-alone computing device or in a network based computing device. For example, the present invention may be implemented in a personal computer, a network computer, a server, or the like. Thus, the following diagrams in **Figures 1-2B** are intended to provide a context for the operations described hereafter.

With reference now to the figures, and in particular with reference to **Figure 1**, a pictorial representation of a distributed data processing system in which the present invention may be implemented is depicted. Distributed data processing system **100** is a network of computers in which the present invention may be implemented. Distributed data processing system **100** contains a network **102**, which is the medium used to provide communications links between various devices and computers connected together within distributed data processing system **100**. Network **102** may include permanent connections, such as wire or fiber optic cables, or temporary connections made through telephone connections.

In the depicted example, a server **104** is connected to network **102** along with storage unit **106**. In addition, clients **108**, **110**, and **112** also are connected to a network **102**. These clients **108**, **110**, and **112** may be, for

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example, personal computers or network computers. For purposes of this application, a network computer is any computer, coupled to a network, which receives a program or other application from another computer coupled to the network. In the depicted example, server **104** provides data, such as boot files, operating system images, and applications to clients **108-112**. Clients **108**, **110**, and **112** are clients to server **104**. Distributed data processing system **100** may include additional servers, clients, and other devices not shown. In the depicted example, distributed data processing system **100** is the Internet with network **102** representing a worldwide collection of networks and gateways that use the TCP/IP suite of protocols to communicate with one another. At the heart of the Internet is a backbone of high-speed data communication lines between major nodes or host computers, consisting of thousands of commercial, government, educational, and other computer systems, that route data and messages. Of course, distributed data processing system **100** also may be implemented as a number of different types of networks, such as, for example, an Intranet or a local area network.

**Figure 1** is intended as an example, and not as an architectural limitation for the processes of the present invention. The present invention may be implemented in the depicted distributed data processing system or modifications thereof as will be readily apparent to those of ordinary skill in the art.

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With reference now to **Figure 2A**, a block diagram of a data processing system which may be implemented as a server, such as server **104** in **Figure 1**, is depicted in accordance to the present invention. Data processing system **200** may be a symmetric multiprocessor (SMP) system including a plurality of processors **202** and **204** connected to system bus **206**. Alternatively, a single processor system may be employed. Also connected to system bus **206** is memory controller/cache **208**, which provides an interface to local memory **209**. I/O Bus Bridge **210** is connected to system bus **206** and provides an interface to I/O bus **212**. Memory controller/cache **208** and I/O Bus Bridge **210** may be integrated as depicted.

Peripheral component interconnect (PCI) bus bridge **214** connected to I/O bus **212** provides an interface to PCI local bus **216**. A modem **218** may be connected to PCI local bus **216**. Typical PCI bus implementations will support four PCI expansion slots or add-in connectors. Communications links to network computers **108-112** in **Figure 1** may be provided through modem **218** and network adapter **220** connected to PCI local bus **216** through add-in boards.

Additional PCI bus bridges **222** and **224** provide interfaces for additional PCI buses **226** and **228**, from which additional modems or network adapters may be supported. In this manner, server **200** allows connections to multiple network computers. A memory mapped graphics adapter **230** and hard disk **232** may also be connected to I/O bus **212** as depicted, either directly or indirectly.

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Those of ordinary skill in the art will appreciate that the hardware depicted in **Figure 2A** may vary. For example, other peripheral devices, such as optical disk drive and the like also may be used in addition or in place of the hardware depicted. The depicted example is not meant to imply architectural limitations with respect to the present invention.

The data processing system depicted in **Figure 2A** may be, for example, an IBM RISC/System 6000 system, a product of International Business Machines Corporation in Armonk, New York, running the Advanced Interactive Executive (AIX) operating system.

With reference now to **Figure 2B**, a block diagram of a data processing system in which the present invention may be implemented is illustrated. Data processing system **250** may be a stand alone computing device or may be an example of a client computer, such as that shown in **Figure 1**. Data processing system **250** employs a peripheral component interconnect (PCI) local bus architecture. Although the depicted example employs a PCI bus, other bus architectures such as Micro Channel and ISA may be used. Processor **252** and main memory **254** are connected to PCI local bus **256** through PCI Bridge **258**. PCI Bridge **258** also may include an integrated memory controller and cache memory for processor **252**. Additional connections to PCI local bus **256** may be made through direct component interconnection or through add-in boards. In the depicted example, local area network (LAN) adapter **260**, SCSI host bus adapter **262**, and expansion bus interface **264** are connected to PCI local



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bus **256** by direct component connection. In contrast, audio adapter **266**, graphics adapter **268**, and audio/video adapter (A/V) **269** are connected to PCI local bus **266** by add-in boards inserted into expansion slots. Expansion bus interface **264** provides a connection for a keyboard and mouse adapter **270**, modem **272**, and additional memory **274**. SCSI host bus adapter **262** provides a connection for hard disk drive **276**, tape drive **278**, CD-ROM **280**, and DVD **282** in the depicted example. Typical PCI local bus implementations will support three or four PCI expansion slots or add-in connectors.

An operating system runs on processor **252** and is used to coordinate and provide control of various components within data processing system **250** in **Figure 2B**. The operating system may be a commercially available operating system such as JavaOS For Business™ or OS/2™, which are available from International Business Machines, Inc. JavaOS is loaded from a server on a network to a network client and supports Java programs and applets. A couple of characteristics of JavaOS that are favorable for performing traces with stack unwinds, as described below, are that JavaOS does not support paging or virtual memory. An object oriented programming system such as Java may run in conjunction with the operating system and may provide calls to the operating system from Java programs or applications executing on data processing system **250**. Instructions for the operating system, the object-oriented operating system, and applications or programs are located on storage devices, such as hard disk drive **276** and may be loaded into main memory **254** for

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execution by processor **252**. Hard disk drives are often absent and memory is constrained when data processing system **250** is used as a network client.

Those of ordinary skill in the art will appreciate that the hardware in **Figure 2B** may vary depending on the implementation. For example, other peripheral devices, such as optical disk drives and the like may be used in addition to or in place of the hardware depicted in **Figure 2B**. The depicted example is not meant to imply architectural limitations with respect to the present invention. For example, the processes of the present invention may be applied to a multiprocessor data processing system.

As described in "APPARATUS AND METHOD FOR AUTONOMIC HARDWARE ASSISTED THREAD STACK TRACKING", incorporated by reference above, a method is provided to store thread tracking information automatically through the use of an allocated thread work area. A trace application or post-processing application may use the thread tracking information to obtain performance information for the trace of a computer program. In addition, the thread tracking information may be used to determine computer program flow during execution of the program in combination with cataloged symbolic data, which is described in further details in the present invention. To present a background, a brief overview of trace applications and post processing applications will be provided.

With reference now to **Figure 3**, a block diagram depicts components used to perform performance traces of

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processes in a data processing system. Trace program **300** is used to profile process **302**. Trace program **300** may be used to record data upon the execution of a hook, which is a specialized piece of code at a specific location in a routine or program in which other routines may be connected. Trace hooks are typically inserted for the purpose of debugging, performance analysis, or enhancing functionality. These trace hooks are employed to send trace data to trace program **300**, which stores the trace data in buffer **304**. In addition, with the hardware assisted thread stack tracking mechanism described in related patent application "APPARATUS AND METHOD FOR AUTONOMIC HARDWARE ASSISTED THREAD STACK TRACKING", which is incorporated by reference above, thread tracking information may be sent automatically to the designated thread work area upon detection of a method entry or exit.

The trace data in buffer **304** may be subsequently stored in trace file **305** or a consolidated buffer when buffer **304** is filled for post-processing. Alternatively, the trace data may be processed in real-time. The trace data in either buffer **304** or trace file **305** is then processed by post-processor **306**. Post-processor **306** processes the trace data to generate an indexed database of symbolic data for loaded modules, as described more fully hereafter.

In a non-Java environment, trace hooks may be employed that aid in the identification of modules that are used in an application under trace. With Java operating systems, trace hooks may be employed that aid in identifying loaded classes and methods.

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In addition, since classes and modules may be loaded and unloaded, these changes may also be identified using trace data. This is especially relevant with "network client" data processing systems, such as those that may operate under Java OS, since classes and jitted methods may be loaded and unloaded more frequently due to the constrained memory and role as a network client. Note that class or module load and unload information are also relevant in embedded application environments, which tend to be memory constrained.

With reference now to **Figure 4**, a diagram depicts various phases in performing a performance trace of the workload running on a system. Subject to memory constraints, the generated trace output may be as long and as detailed as the analyst requires for the purpose of profiling a particular program.

An initialization phase **400** is used to capture the state of the client machine at the time tracing is initiated. This trace initialization data includes trace records that identify all existing threads, all loaded classes (modules), and all methods (sections) for the loaded classes (modules). Records from trace data captured from hooks are written to indicate thread switches, interrupts, and loading and unloading of classes (modules) and "jitted" methods (sections).

Any class (module) which is loaded has trace records that indicate the name of the class (module) and its methods (sections). Numeric IDs may be used as identifiers for threads, classes, and methods. These IDs are associated with names that have been output in the

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trace records. A trace record is written to indicate when all of the start up information has been written.

During the profiling phase **402**, trace records are written to a trace buffer or trace file. In the present invention, a trace buffer may have a combination of types of records, such as those that may originate from a trace hook executed in response to a particular type of event, e.g., a method entry or method exit, and those that may originate from a stack walking function executed in response to a timer interrupt, e.g., a stack unwind record, also called a call stack record.

For example, the following operations may occur during the profiling phase if the user of the profiling utility has requested sample-based profiling information. Each time a particular type of timer interrupt occurs, a trace record is written, which indicates the system program counter. This system program counter may be used to identify the routine that is interrupted. In the depicted example, a timer interrupt is used to initiate gathering of trace data. Of course, other types of interrupts may be used other than timer interrupts. Interrupts based on a programmed performance monitor event or other types of periodic events may be employed, for example.

In the post-processing phase **404**, the data collected in the trace buffer is processed or sent to a trace file or a consolidated buffer if the trace buffer is filled for post-processing. In one configuration, the file may be sent to a server, which determines the profile for the processes on the client machine. Of course, depending on

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available resources, the post-processing also may be performed on the client machine.

As mentioned previously, the present invention provides a method, apparatus, and computer instructions for determining computer program flows autonomically using hardware assisted thread stack tracking and cataloged symbolic data. One embodiment of the present invention provides three hardware registers: a work area register, which includes a pointer pointing to the beginning of the allocated thread work area; a current pointer register, which includes a pointer pointing to the location of the last written call stack entry; and a work area length register, which indicates the length of the work area. Alternatively, instead of the work area length register a pointer pointing to the end of the allocated thread work area may be used.

With the present invention, the functionality of microcode currently existing in a processor is extended by programming instructions for establishing work areas and monitoring the execution of instructions to determine how to update the thread tracking information in the thread work areas. Microcode is a permanent memory that holds the elementary circuit operations a computer must perform for each instruction in its instruction set. Microcode acts as a translation layer between the instruction and the electronic level of the computer.

In a preferred embodiment, when a new thread is spawned during execution of a computer program, the operating system or the device driver of the client device, such as data processing system 250 in **Figure 2**,

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instructs the processor to allocate a new thread work area in memory. The work area register is set with a pointer pointing to the newly allocated thread work area. Initially, the work length register is set with a fixed length as notified by the operating system during initialization phase.

As the program is executed, thread tracking information, including call stack entries, are written to the designated thread work area by microcode of the processor in a manner described in the related patent application "APPARATUS AND METHOD FOR AUTONOMIC HARDWARE ASSISTED THREAD STACK TRACKING", which is incorporated by reference above. Upon detection of a method entry or exit, call stack entries are written to the designated thread work area in two modes. In one mode, entries are written continuously to the call stack. Alternatively, in a call stack mode, entries are pushed onto the call stack when a method entry is detected and popped off the call stack when a method exit is detected. A call stack entry includes information for a method entry/exit during execution of a spawned thread, such as a timestamp when the method is called or returned, address from which a call is made, address of the called method, and a return-to address. The operating system notifies the processor to update the pointer in the current pointer register with a new location each time a call stack entry is written.

Subsequently when a context switch occurs, meaning when a different thread is dispatched during executing of the computer program, values in the three registers are

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saved away by the processor in a context save area, which stores context information for a particular thread. The context save area may be within the thread work area or other location in memory. Upon reactivation of the thread by the program, the operating system or device driver instructs the processor to restore saved values from the context save area to the three registers.

Prior to writing each call stack entry, the mechanism of the present invention determines if the designated thread work area is about to overflow based on pointers stored in the work area length register and the current pointer register. An overflow may occur, for example, when the call stack is filled as entries are written to the stack. If an overflow is about to occur, the present invention sends an interrupt to the operating system or a performance monitoring application, which is an application that monitors performance of the system.

During the post-processing phase, which may occur during or after the profiling phase, a trace application or a post-processing application may utilize the call stack data for determining computer program flow. The trace application or the post-processing application may perform, in one mode of operation, a full trace of a computer program, including all executing threads, by reading stored call stack data from the consolidated buffer. The stored call stack data includes call and return operations during execution of each thread.

In this mode, the operating system, or the performance monitoring application, copies the call stack entries from the designated thread work area to a



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consolidated buffer when the thread work area is filled. A consolidated buffer is similar to a trace buffer except that the consolidated buffer is written to only when the stack is filled or when the data is purposely copied by the operating system or the device driver. The data in the consolidated buffer may eventually be copied to a disk or other buffer within the user space.

Alternatively, a sample trace of a computer program may be performed by a trace application in a call stack mode. In the call stack mode, entries are pushed onto and popped from the call stack as call or return operations are detected during execution of a thread. In this mode, the trace application wakes up by an interrupt, which may be a timer interrupt that expires periodically being generated. The trace application then requests the operating system to take a snapshot of the call stack entries in the thread work area in order to determine the current program flow. Similar to the above, the operating system or the device driver may then copy the call stack entries from the thread work area(s) to the consolidated buffer.

In either mode of operation, the microcode of the processor may be programmed to store additional information when writing call stack entries. Examples of additional information include time stamps and values of selected performance monitoring counters. A performance monitoring counter is a hardware counter placed inside of a processor to monitor performance of the system. The performance monitoring counters may be programmed to count various events, such as, instructions completed,

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cache misses, etc. By including additional information, such as instructions completed, in the call stack entries, other useful program related information may be recorded for user analysis. This additional information may be compressed or consolidated with other information in the call stack entry when the entry is written to the call stack or when the call stack entries are copied from the thread work area to the consolidated buffer during post-processing.

Turning now to **Figure 5A**, a flowchart illustrating an exemplary process of initiating hardware thread stack tracking is depicted in accordance with a preferred embodiment of the present invention. The process begins when the trace of code execution is initiated by a user (step **502**). Next, the control bit for storing thread tracking information is then set in the processor (step **504**). The control bit is located in a control register of the processor. By setting the control bit, hardware thread tracking is enabled. Alternatively, other indications of hardware thread tracking may be used, such as having a non-zero value in the work area register or a non-zero value in the work area length register, for example. When a new thread is spawned during code execution, the operating system or device driver allocates a work area for the new thread (step **506**) and sets the work area register to point to the beginning address and to store the length of newly allocated work area in the work area length register (step **508**). Initially, the size of the work area is fixed, but may be extended if necessary. The operation then terminates.

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Turning now to **Figure 5B**, a flowchart illustrating an exemplary process of writing hardware thread tracking information to the allocated thread work area as events occur in one mode of operation is depicted in accordance with a preferred embodiment of the present invention. The process begins when the processor detects a call or return operation (step **512**). The processor may then identify the location of the work area using the value of work area register added to the value of the current pointer register (step **514**).

Next, prior to writing an entry for the call or return operation, a determination is made by the trace application as to whether an overflow occurs in the thread work area (step **516**). The determination is based on the value of the current pointer register, the work area length register, and the amount of data to be written.

If an overflow is about to occur, an interrupt is sent by the trace application to the operating system or a performance monitoring application (step **518**) in order to copy call stack data from the designated thread work area to the consolidated buffer and reset the current pointer register (step **520**). If no overflow is about to occur, the process continues to step **522**.

At step **522**, the processor writes the call stack entry for the call or return operation to the designated thread work area. The trace application then sets the current pointer register pointer to the location of the last entry written in the designated work area (step **524**). The operation then terminates.

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When a different thread is dispatched the values of the current hardware control registers are saved away in a context save area, and previous values or new values for the current thread are restored/generated and stored in the three registers. Thus, the process repeats for the newly dispatched thread beginning at step **512**. In this mode of operation, new entries for either a call or a return operation are pushed onto the stack and thus, a full trace of the computer program is performed by the trace application to capture both call and return operations.

Turning next to **Figure 5C**, a flowchart illustrating an exemplary process of writing hardware thread tracking information to the allocated thread work area, as events occur in a call stack mode of operation, is depicted in accordance with a preferred embodiment of the present invention. The process begins when the processor detects a call or return operation (step **522**). A determination is then made by the processor as to whether the operation is a call or return (step **524**).

If the operation is a return operation, the processor identifies the location of a designated work area for the thread using the pointer to the work area register (step **540**). The processor then pops the last entry off the call stack in the designated thread work area (step **542**) and the process continues to step **534**.

However, if the operation is a call operation, the processor may then identify a location of the work area using the pointer to the work area register (step **526**). Next, prior to writing an entry for the call operation, a

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determination is then made by the trace application as to whether an overflow is about to occur in the thread work area (step **528**). The determination is based on the value of the current pointer register, the work area length register, and the amount of data to be written. If no overflow is about to occur, the process continues to step **534**. However, if an overflow is about to occur, an interrupt is sent by the hardware to the operating system (step **530**) or performance monitoring application in order to copy call stack data from the designated thread work area to the consolidated buffer and reset the pointer in the current pointer register (step **532**). The process then continues to step **534**.

At step **534**, the processor writes the call stack entry for the call operation to the designated thread work area. The trace application then sets the pointer in the current pointer register to point to the location of the last entry written in the designated work area (step **536**). The operation then terminates.

When a different thread is dispatched the values of the current hardware control registers are saved away in a context save area and previous values or new values for the current thread are stored in the hardware control registers. Thus, the process repeats for the current beginning at step **522**. In a call stack mode of operation, a sample trace of the computer program is performed to capture only call operations.

With reference now to **Figure 6**, a diagram illustrating primary operational components according to one exemplary embodiment of the present invention is

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depicted. During the initialization phase of a performance tracing program, such as the initialization phase **400** in **Figure 4**, trace application **620** may instruct the operating system **640** regarding size of the thread work area to be allocated for threads of the computer program. The size of the thread work area that is to be allocated for each thread may be extended when necessary. Device driver **642** of operating system **640** may set a control bit in the processor **610** to indicate that hardware thread tracking is to be performed. Operating system **640** may then allocate a portion of the system memory **630** for use as the work areas for thread tracking information.

When a new thread is created during execution of the computer program, operating system **640** allocates a thread work area, such as thread work area **632**, for the new thread in the computer program, in which the thread's call stack information is to be stored. Each thread corresponds to a thread work area. Therefore, thread work areas **632-638** corresponds to four different threads. The beginning address of the allocated thread work area is stored in work area register **614** and the length for the work area is stored in work area length register **618**, both of which are part of control registers **602** of processor **610**.

In addition, current pointer register **616** is provided within control registers **602**. Current pointer register **616** is used to identify the location of the work area to which an entry is written. In this way, the

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currently active location of the thread work area may be identified.

When a different thread is created during execution of the computer program, hence when a thread context switch occurs, the values in hardware registers **614-618** may be updated. The values are first saved by the operating system **640** or device driver **642** to a context save area, which has the context of the current thread. The context save area may be within thread work area **632** or another dedicated location (not shown) in memory **630**. Next, operating system **640** or device driver **642** restores previously saved values, or generates new values, for the initiated thread and saves them in hardware registers **614-618**.

As described previously, the present invention extends current functionality of the microcode in a processor to include the additional functionality and operations discussed herein. For each existing thread, operating system **640** allocates a portion of memory **630** for use in storing one or more thread work areas. This portion of memory **630** has a size equal to the fixed size determined in the initialization phase. Microcode **612** then begins to monitor the instructions executed by processor **610** to determine if a new thread is spawned, if a memory overflow occurs, if a method/routine entry (call) instruction is executed, and if a method/routine exit (return) instruction is executed.

Also described above, if a new thread is spawned, a new thread work area, such as thread work area **634**, in the system memory **630** may be created and a context switch

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may be communicated to the microcode **612** so that the values in hardware registers **614-618** identifying the last work area accessed may be updated to point to the new thread work area.

If memory overflow occurs, operating system **640** or device driver **642** may capture call stack information in the thread work area for the associated thread instead of extending the thread work area. As described in the related patent application "APPARATUS AND METHOD FOR AUTONOMIC HARDWARE ASSISTED THREAD STACK TRACKING, which is incorporated by reference above, the thread work area may be extended when an interrupt is sent from microcode **612** of processor **610** to operating system **640** in response to a thread work area overflow. Operating system **640** may extend thread work area by including an extension area. Work area register **614**, current pointer register **616**, and the work area length register **618** may all be impacted as a result of the extension.

However, in the present invention, instead of extending the thread work area in response to an overflow, the call stack information may be captured by operating system **640** to a new thread work area, such as trace buffer **624** or trace file **622**, which is accessible by a trace application or a post-processing application.

If a method/routine entry (call) instruction is executed, then a call stack entry for the method/routine is created by the processor in the appropriate thread work area indicating the entry of a method/routine, i.e. a call stack entry is pushed onto the call stack by the processor.



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If a method/routine exit (return) instruction is executed, a call stack entry for the exiting of the method/routine may be entered by the processor into the call stack of the work area in one mode of operation or popped off from the call stack in another mode of operation, which is referred to previously as the call stack mode.

If a new thread is spawned during the execution of the computer program that is being traced, and thread tracking is enabled in the processor **610** by the setting of the control bit in the processor **610**, then a new thread work area is needed in order to track the thread execution. A new thread may be determined to have been spawned by the communication of a context switch by the operating system **640**. Similar to the allocation of work areas during initialization, the operating system **640** may allocate a new thread work area, such as thread work area **632**, for the new thread by setting work area register **614** of control registers **602** to point to the beginning of the work area and designate the length of the thread work area in work area length register **618** of control registers **602**.

Thereafter, when the new thread causes an event to occur, such as entry or exit of a method/routine, an entry will be written by the processor to the work area for the new thread having the necessary information for use by trace application **620** or post-processing program **628**. Current pointer register **616** is updated by microcode **612** of processor **610** with pointer pointing to location of the last written entry.

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If a method/routine entry instruction is executed by processor **610**, as determined by whether the instruction executed by the processor **610** is a "call" instruction or not, microcode **612** determines if thread tracking is enabled in the processor **610**. That is, microcode **612** determines if the control bit identifying thread tracking to be enabled is set. If the control bit is set and a method/routine entry instruction is executed by processor **610**, microcode **612** determines that a call stack event has occurred that requires the creation and storage of a call stack entry in the thread work area for the associated thread.

Microcode **612** identifies the beginning address of the thread work area for the thread by retrieving the address information from work area register **614** of control registers **602** and determines if there is enough room in the thread work area to write the call stack entry for the event. This may be determined by comparing the length of the thread work area, as designated in work area length register **618**, to the location of the last entry written to the call stack in the thread work area, as designated in current pointer register **616**. If the thread work area has enough remaining storage, a call stack entry for the event is generated and stored in the thread work area for the thread, e.g., thread work area **632**. This call stack entry may include, for example, the address of the method/routine being called.

If the thread work area for the thread, e.g., thread work area **632**, does not have sufficient storage capacity for a new call stack entry, then microcode **612** identifies

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the condition as a work area or memory overflow. As a result, microcode **612** sends an interrupt to the trace application code **620** via operating system **640** indicating the work area overflow. In response, trace application code **620** may instruct operating system **640** to capture call stack information in the thread work area for the thread to a new thread work area, such as trace buffer **624** or trace file **622**. In response to the instruction to capture the work area for the thread, operating system **640** copies the call stack information and resets values in hardware registers **614-618**.

Similar to the operation above with regard to the entry of a method/routine, processor **610** may detect that a method/routine is exited by the execution of a "return" instruction in the code of the computer program. Upon the detection of a "return" instruction, the present invention may add an additional entry to the call stack designating the exit of the method/routine in one mode of operation. In this mode, every method/routine entered and exited during execution of the thread is captured.

Alternatively, the present invention may remove entries for methods/routines that are exited from the call stack in another mode of operation, referred to as call stack mode, to only capture method/routine that entered during execution of the thread.

Thus, as processor **610** executes instructions of the computer program under the trace, operating system **640** automatically allocates new thread work areas for newly spawned threads, writes call stack entries into thread work areas in response to the detection of an entry/exit

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method/routine event, and captures call stack information when an overflow occurs. As a result, hardware mechanisms of the present invention help to alleviate some of the burden of performing these operations entirely in software. Moreover, since the hardware may operate virtually independently of the trace application and computer program under trace, with regard to these operations, these operations may be performed regardless of the particular trace application or computer program that is executing. Furthermore, the computer program under trace need not be instrumented to obtain the call stack information since this information is automatically obtained by the processor once the trace application indicates that thread tracking is to be enabled.

It should be appreciated that the above operations of the present invention may be initiated at any time during tracing of a computer program. Thus, in one mode of operation, a trace application may wake up as a result of a filled call stack or a timer interrupt, the mechanism of the present invention is initiated to capture call stack information from the thread work area. Alternatively, in a call stack mode, a situation may be present in which the mechanism of the present invention is initiated while method calls are currently outstanding, i.e., a method call has been made and the present invention is initiated prior to the called method being exited. In other words, when in call stack mode, a return operation may be performed without a call operation having been made while the present invention is

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active. In these situations, such return operations are handled as a no op, that is, no operation.

As described in "APPARATUS AND METHOD FOR CATALOGING SYMBOLIC DATA FOR USE IN PERFORMANCE ANALYSIS OF COMPUTER PROGRAMS", incorporated by reference above, a method is provided for post-processing performance trace data recorded in trace buffer **624** or trace file **622**. A merged symbol file, such as merge symbol file **630**, is generated for a computer program, or application, under trace. Merged symbol file **630** comprises symbolic data for modules obtained from map files, debug files, non-stripped versions of modules, and other symbolic data files. The merged symbol file contains information useful in performing symbolic resolution of address information in trace files for each instance of a module, such as checksum, timestamp, fully qualified path to the module, length of the module, etc.

During post processing of the trace information generated by a performance trace of a computer program, symbolic information stored in merged symbol file **630** is compared to the trace information stored in trace file **622**. The trace information includes information identifying the modules that were called during the trace of the computer application. This trace information, which may be obtained using the hardware thread tracking mechanisms previously described, and the merged symbol file are used to produce reports. The correct symbolic information in merged symbol file **630** for the modules used in the trace is identified based on a number of validating criteria.

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The correct symbolic information for the required modules may then be stored as an indexed symbolic database, for example, indexed symbolic database **626**, that is indexed using process identifiers and address identifiers. The indexed database of symbolic information may be stored as a separate file or as a separate portion of a trace file for the computer application. Indexed symbolic database **626** may then be used to resolve address information into corresponding symbolic information when providing the trace information for use by a user.

As described above, the symbolic information provides symbolic data for loaded modules/processes, i.e. called module or processes, of the application under trace. As a result of the symbolic resolution, indexed symbolic database **626** for the loaded/called

modules/processes is generated by either the trace application **620** or the post-processing program **628**.

The indexed database entries may be indexed based on any searchable value. In a preferred embodiment, the indexed database is indexed based on the process identifier (pid) and the segment load address, however, other searchable indices may be used without departing from the spirit and scope of the present invention.

Once indexed symbolic database **626** is generated, trace application **620** or post-processing application **628** may search indexed symbolic database **626** for symbolic information that matches the process identifier (pid) and the address of the method/routine called or returned by each thread. When a match is found, a call sequence may

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be generated using symbolic data that represents the computer program flow.

Turning now to **Figure 7**, a flowchart outlining an exemplary operation of the data processing system of the present invention when dynamically generating an indexed database of symbolic data based on performance trace data stored in the trace buffer is depicted in accordance with a preferred embodiment of the present invention. The steps shown in **Figure 7** are repeated for new performance trace data written to the trace buffer. In this way, an indexed database of symbolic data is dynamically created as the application is under trace.

As shown in **Figure 7**, the operation starts with a performance trace of the computer program being performed (step **702**) and a trace file being generated (step **704**). The trace file is searched for loaded/called module entries (step **706**) and symbolic data for the loaded/called modules is obtained (step **708**). The symbolic data is preferably obtained from a merged symbol file. These steps are normally performed by a trace application.

Once the symbolic data is obtained for the loaded/called modules, the symbolic data is stored as a separate section of the trace file containing only the symbolic data for the loaded modules (step **710**). This symbolic data is then indexed to generate an indexed database of symbolic data for the loaded modules as a separate section of the trace file (step **712**) and the process terminates thereafter.

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Thus, an indexed database of symbolic data for loaded modules is obtained by gathering symbolic data from a plurality of sources into a merged symbol file, such as merged symbol file **630** in **Figure 6**, and then comparing this merged symbol file with performance trace data that is stored in either the trace buffer or in a trace file on a storage device. Matching symbolic data is then written to an indexed database in correspondence with the performance trace data.

Turning next to **Figure 8A**, a diagram illustrating interactions between components used in the present invention during post-processing by a trace application is depicted in accordance with a preferred embodiment of the present invention. Post-processing may actually occur during or after the tracing phase. In this example, post-processing is performed during the performance trace by trace application **802**. The operation starts when trace application **802** informs operating system **804** of the size of the work areas for storing thread tracking information, e.g., call stack information (operation **812**). Next, trace application **802** instructs processor **806** to set the thread tracking enabled control bit in the control bit register (operation **814**).

The operating system **804** then allocates the new work areas for new threads (operation **816**) of the computer program by allocating address ranges in memory **808** for each thread. Operating system **804** then instructs processor **806** to set the work area register to point to the beginning address and stores the length for the work



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area, which is initially fixed, in the work area length register (operation **818**). Thereafter, as call stack events occur, processor **806** writes call stack entries to the appropriate work areas in memory **808** (operation **820**).

At some time later, a wakeup of trace application **802** is caused by an interrupt (operation **822**). The interrupt may be initiated when the trace buffer is filled or by a periodic timer. Trace application **802** then requests the thread call stack information (operation **824**) from processor **806**. Next, trace application **802** notifies processor **806** to retrieve call stack information (operation **826**) via operating system **804** using the pointer stored in the current pointer register. The call stack information retrieved may be copied to a consolidated buffer that is accessible in the application space. Once the call stack entries are copied to the consolidated buffer, the operating system or the performance monitoring application maps each thread back to the process to which the thread belongs.

The call stack information for the threads of interest may then be processed by trace application **802**. This is accomplished by reading the call stack entries from the consolidated buffer to identify the thread-process relationship. Typically, when a thread is created, it is created within a process. The operating system may provide an interface to identify the process and another interface to identify the thread. In addition, the thread-process information is known by the operating system at thread creation time.

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Alternatively, at dispatch time, which is when a thread is dispatched and starts executing, both the process identifier and corresponding thread identifier are known to the operating system. This information is known to the operating system, because the addresses of the dispatched process and thread have fixed locations or symbolic names. When the dispatcher chooses the process and thread to dispatch, a trace record may be written by the operating system or kernel extension identifying the process and thread being dispatched. From this trace record, a process identifier and a thread identifier may be retrieved.

Thus, trace application **802** may request symbolic data (operation **828**) from the indexed symbolic database **810**. A search is performed by trace application **802** for symbolic data. An example of retrieved symbolic data is "C:\System\user.dll(function1)". The search for symbolic data is based on the process identifier and address of the method calls or returns for each thread. The address of a call operation is the address to where the processor will transfer control when the call operation is executed. Typically, a "from" and a "to" address are written to the call stack in the thread work area. An example of an address is "0x80140000". This address information may be in a compressed form when it is written to the call stack along with additional information such as time stamps and performance monitoring counter values. Alternatively, a consolidation and/or compression may be made at the time

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the call stack data is copied from the thread work area to the consolidated buffer.

Once the symbolic data is retrieved for the call stack information (operation **830**) trace application **802** performs symbolic resolution (operation **832**). Lastly, trace application **802** generates a call tree or sequence using the symbolic data (operation **834**), which depicts the computer program flow.

Alternatively, the post-processing may be performed by a post-processing program after the profiling phase. Turning now to **Figure 8B**, a diagram illustrating interactions between components used in the present invention during post-processing by a post-processing application is depicted in accordance with a preferred embodiment of the present invention. As shown in **Figure 8B**, operations **854-870** occur in a similar manner as operations **812-826** described in **Figure 8A**. However, instead of trace application **842**, post-processing application **850** now performs post-processing of the call stack information retrieved from processor **846** after the profiling or tracing phase has taken place.

Post-processing application **850** reads call stack data from a trace buffer or file (operation **872**) retrieved by trace application **842**. The trace buffer may be the consolidated buffer, which includes call stack data copied from thread work areas during execution of the program code. Once the call stack data is read from the consolidated buffer, post-processing application **850** may request symbolic data (operation **874**) from indexed symbolic database **852** based on the process id and the

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address of method calls or returns for each thread. Once symbolic data is retrieved (operation **876**), post-processing application **850** may perform symbolic resolution (operation **878**) and generate a call tree or sequence of the computer program based on the symbolic data (operation **880**).

Turning next to **Figure 9A**, a flowchart process illustrating an exemplary process of determining computer program flow autonomically using thread stack tracking information and cataloged symbolic data when post-processing is performed during profiling is depicted in accordance with a preferred embodiment of the present invention. In this example, post-processing is performed at run time by the trace application. The process begins when a trace application wakes up periodically (step **902**). The trace application wakes up periodically when a timer expires or when the trace buffer is filled.

Upon waking up, the trace application requests call stack data from the processor (step **904**). The processor identifies the address of the thread work area using the pointer to the work area register. Next, the device driver in the operating system copies the call stack data to a trace buffer or file (step **906**). The trace buffer may be a consolidated buffer where call stack data for each thread may be stored. When the call stack data is copied from the thread work area, other processing may occur, such as, compressing or consolidating the call stack data with additional information, such as, time stamps and performance monitoring counter values. Next,

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the trace application reads the call stack data in the trace buffer or consolidated buffer (step **908**).

In order to retrieve symbolic data, the device driver, the operating system, or a performance monitoring application maps each thread to a process (step **910**). The mapping is performed by locating a process identifier (pid) that corresponds to the thread identifier specified in the call stack data. Once the mapping is complete, the trace application searches the indexed symbolic database for symbolic data that matches process id and address of each method call or return for each thread (step **912**). Based on the retrieved symbolic data, a call tree or sequence is generated by the trace application that describes the execution flows of a computer program (step **914**). The operation then terminates.

In an alternative embodiment, rather than searching the indexed symbolic database, other methods may be used to retrieve the symbolic data. These methods include examining the loaded/called module itself if the address of the loaded/called module on a disk is known, examining other symbolic data in the same directory as the load/called module, and examining symbolic data in a shadow directory. A shadow directory is a directory that resides in a separated location on the same data processing system.

Turning next to **Figure 9B**, a flowchart process illustrating an exemplary process of determining computer program flows autonomically using thread stack tracking information and cataloged symbolic data when post-processing is performed after profiling is depicted in

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accordance with a preferred embodiment of the present invention. In this example, post-processing is performed by the post-processing application after profiling phase. The process begins when the post-processing application requests call stack data from the processor (step 920). The processor identifies location of the thread work area using the pointer to the work area register. Once the thread work area location is identified, the device driver in the operating system copies the call stack data to a trace buffer or trace file (step 922). The trace buffer may be a consolidated buffer where call stack data for each thread is stored. The post-processing application then reads the call stack data from the trace or consolidated buffer (step 924).

Similar to the process in **Figure 9A**, the device driver, the operating system, or the performance monitoring application maps each thread to a process (step 926) in order to retrieve symbolic data. Once the mapping is complete, the post-processing application searches the indexed symbolic database for symbolic data that matches the process identifier (pid) and the address of each call or return for each thread (step 928). Once the symbolic data is retrieved, the post-processing application generates a call tree or sequence using the retrieved symbolic data (step 930) that describes the execution flows of the computer program. The operation then terminates.

Turning next to **Figure 10**, a diagram illustrating an example indexed symbolic database, example call stack entries, and an example call sequence is depicted in

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accordance with a preferred embodiment of the present invention. Indexed database **1000** includes entries **1010**. Each entry includes an index, such as index **1012**. Index **1012** is represented using a process identifier and address for the method call or return (pid:address). Corresponding to each index is the symbolic data that represents the subroutine name. For example, for index **1012** with a pid of 1 and an address of 80140000, corresponding symbolic data **1020** is C:\SYSTEM\foo.exe(subroutine1). Thus, when a particular pid:address is encountered in the performance trace file, the pid:address may be converted into a particular symbolic location of a particular location within an executable file. The symbol itself corresponds to a subroutine (or a method).

When a trace application wakes up or when a post-processing application requests call stack data, the operating system or device driver copies the call stack data from the thread work area to a trace or consolidated buffer. In this example, thread 1 call stack **1030** is copied. When the device driver, the operating system or a performance monitoring application maps thread 1 to a process, it is mapped to pid of 1. Thread 1 call stack **1030** includes 5 entries, entries **1040**. Entries **1040** are arranged in the order the method is called or returned. For example, entry **1042** is called prior to entry **1044** when thread 1 is executed. Thus, entries **1040** depict the computer program flow when thread 1 is executed.

Based on entries **1010** in indexed symbolic database **1000** and entries **1040** in thread 1 call stack **1030**, trace

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application or post-processing application may generate call tree or sequence **1050** after symbolic resolution is performed for pid 1. In call sequence **1050**, method C:\SYSTEM\foo.exe(subroutine1) **1052** is first called by pid 1. Subsequently, method C:\User\foo.dll(subroutine1) **1054** is called, followed by method C:\SYSTEM\foo.exe(subroutine2) **1056** and C:\User\foo.dll(subroutine2) **1058**.

Thus, using the call stack data copied for a thread of the computer program, along with mapping of a thread to a process, the index symbolic database is searched for symbolic data that corresponds to each thread of a computer program. Hence, a call tree or sequence may be generated using the symbolic data that represents the computer program flow.

In summary, the present invention provides hardware registers necessary to manage thread work areas in memory, which store call stack information for events that occur during execution of a computer program. In addition, the present invention extends the functionality of microcode in existing processors to manage updates of the hardware registers and allocation of thread work areas. The microcode may be programmed to store additional information, such as, time stamps and values of performance monitoring counters, in call stack entries of the thread work area. By storing additional information, such as, instructions completed, the call stack data may include instructions that are completed for each subroutine that is executed in each thread of a computer program. This data provides valuable program



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related information to the user. These innovative mechanisms aid in determining computer program flow more efficiently without the need for a large memory footprint. Furthermore, the mechanisms of the present invention enable the integrated use of an indexed symbolic database and thread stack tracking information to generate symbolic data for the computer program flow that is readable by a user.

It is important to note that while the present invention has been described in the context of a fully functioning data processing system, those of ordinary skill in the art will appreciate that the processes of the present invention are capable of being distributed in the form of a computer readable medium of instructions and a variety of forms and that the present invention applies equally regardless of the particular type of signal bearing media actually used to carry out the distribution. Examples of computer readable media include recordable-type media, such as a floppy disk, a hard disk drive, a RAM, CD-ROMs, DVD-ROMs, and transmission-type media, such as digital and analog communications links, wired or wireless communications links using transmission forms, such as, for example, radio frequency and light wave transmissions. The computer readable media may take the form of coded formats that are decoded for actual use in a particular data processing system.

The description of the present invention has been presented for purposes of illustration and description, and is not intended to be exhaustive or limited to the

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invention in the form disclosed. Many modifications and variations will be apparent to those of ordinary skill in the art. The embodiment was chosen and described in order to best explain the principles of the invention, the practical application, and to enable others of ordinary skill in the art to understand the invention for various embodiments with various modifications as are suited to the particular use contemplated.